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Abstract: The proposed SHiP experiment located at the CERN SPS will search for feebly interacting particles with masses below 10 GeV/c. A veto timing detector will reject combinatorial di-muon backgrounds by requiring event to be coincident in time within 100 ps. The baseline option for the timing detector consist of scintillating bars read out by arrays of silicon photomultipliers. The detector comprises 546 bars of EJ200 scintillating material with dimensions 168 cm 6 cm 1 cm broken into three columns and covering an active area of 5 m 10 m. The end of each bar is read out by an array of eight silicon photomultipliers attached to custom PCBs and subsequently read out by a DAQ system based on a SAMPIC chip. We present test beam results on a single column 22 bar prototype for the SHiP timing detector. Measurements were taken at the T10 beam line of the CERN PS. A timing resolution across the detector is found to be about 90 ps. The particle identification capability using a time of flight method is also demonstrated.

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A prototype for the SHiP timing detector

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ABSTRACT

The proposed SHiP experiment located at the CERN SPS will search for feebly interacting particles with masses below 10 GeV/c^2. A veto timing detector will reject combinatorial di-muon backgrounds by requiring event to be coincident in time within 100 ps. The baseline option for the timing detector consist of scintillating bars read out by arrays of silicon photomultipliers. The detector comprises 546 bars of EJ200 scintillating material with dimensions 168 cm × 6 cm × 1 cm broken into three columns and covering an active area of 5 m × 10 m. The end of each bar is read out by an array of eight silicon photomultipliers attached to custom PCBs and subsequently read out by a DAQ system based on a SAMPIC chip. We present test beam results on a single column 22 bar prototype for the SHiP timing detector. Measurements were taken at the T10 beam line of the CERN PS. A timing resolution across the detector is found to be about 90 ps. The particle identification capability using a time of flight method is also demonstrated.

1. Introduction

SHiP (Search for Hidden Particles) is a proposed general purpose fixed target experiment to be located at the north area of the CERN SPS [1]. It will study tau neutrino production and search for feebly interacting particles with masses below 10 GeV/c^2 [2]. The experiment will comprise a heavy target followed by a hadron stopper, magnetic muon shield [3] and a dedicated neutrino detector. Downstream of the neutrino detector is a Hidden Sector (HS) detector, consisting of an evacuated vacuum vessel, spectrometer, veto timing detector, calorimeters and a muon detector.

The HS detector is designed to ensure sufficient background rejection through background taggers surrounding the decay volume and a dedicated downstream veto timing detector. The timing detector will be placed in front of the calorimeters following the magnetic spectrometer and cover an area of 5 m × 10 m. Along with kinematic cuts and the background taggers, requiring events to be coincident in time within 100 ps is sufficient to suppress the combinatorial di-muon background. Two options have been proposed for the timing detector; Multigap Resistive Plate Chambers (MRPC) [4,5] and scintillating bars read out by silicon photomultipliers (SiPM) [6–9]. The latter is the focus of this paper.

The scintillator option for the timing detector consists of staggered EJ200 plastic scintillating bars arranged into 3 columns, each broken into 182 rows. Each bar has dimensions of 168 cm × 6 cm × 1 cm and is read out of both ends by an array of eight 6 mm × 6 mm SiPMs soldered to custom pre-amplifier PCBs. There is a 5 mm overlap between bars in the vertical direction and 1 cm overlap in the horizontal direction. The DAQ is based on the SAMPIC ASIC, a 16-channel waveform digitizer and TDC [10]. The first layer of the readout comprises a concentrator board for each column that groups 6 SAMPIC modules, containing 4 ASICS each, with a total data rate of about 1 Gbit/s. A second layer will group the three layer-one boards for a total data rate of 3 Gbit/s. In total the detector comprises 546 bars, corresponding to 8736 SiPMs and 1092 readout channels. A schematic of the timing detector and illustration of the readout scheme is shown in Fig. 1.

The material for the scintillator plastic was chosen by the timing resolution requirements. EJ200 is found to have the right combination of light output, attenuation length (3.8 m) and fast timing (rise time of 0.9 ns and decay time of 2.1 ns). The wavelength emission spectrum peaks at 425 nm, closely matching the SiPMs spectral response (450 nm). The number of photons generated by a minimum-ionizing particle crossing 1 cm scintillator is $\mathcal{O}(10^4)$. The bars will be wrapped in an aluminum foil and a black plastic stretch film on top to ensure opacity.

2. The prototype and measurement setup

In July 2018 a 22 bar prototype, seen in the left of Fig. 2, consisting of a single column of vertically staggered bars covering an active area of 168 cm × 120 cm was constructed [9]. Each bar had dimensions of 168 cm × 6 cm × 1 cm aside from the top and bottom bar which had the same cross-section but were 18 cm shorter in length. Light generated in each bar was collected by an array of 8 Hamamatsu S13360-6050PE

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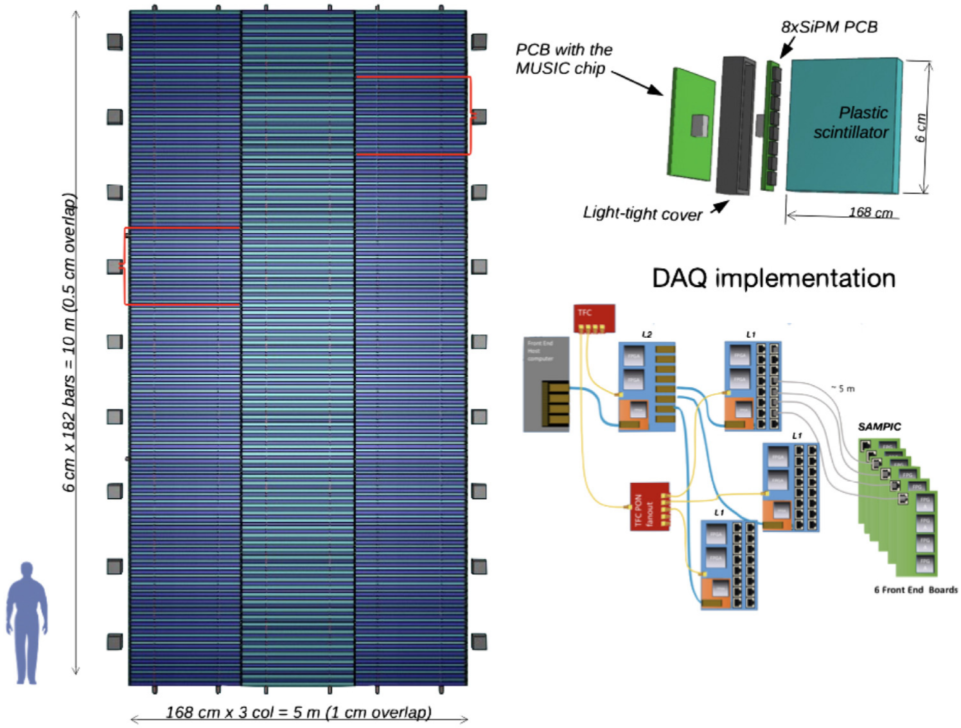

Fig. 1. Left: Representation of the SHiP timing detector. Right: Connection of the bars to the SiPMs and readout PCBs and DAQ implementation scheme.

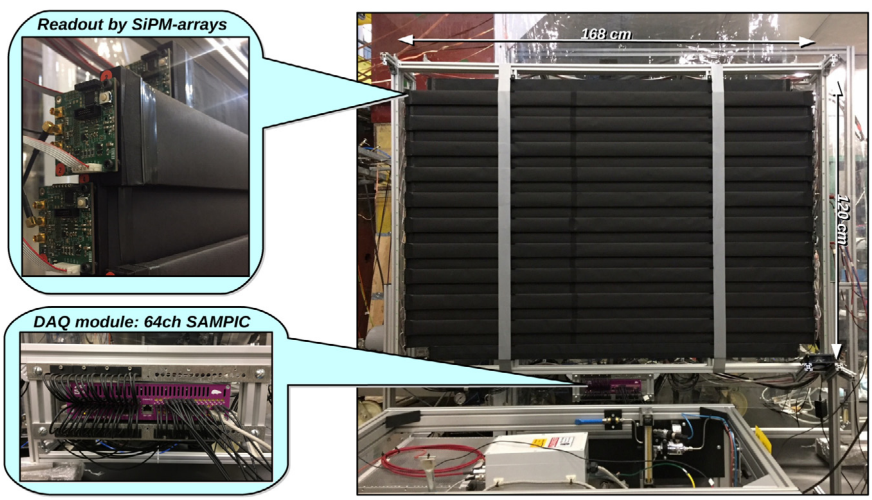

Fig. 2. The timing detector prototype as seen in the testbeam area.

SiPMs biased to an over voltage of 5 V. Each array was mounted onto a custom PCB which was read out by an MUSIC chip [11].

MUSIC is an 8 channel ASIC for SiPM anode readout is based on a novel low input impedance current conveyor. The ASIC has been designed for the readout of SiPM arrays for the Cherenkov Telescope Array (CTA) cameras [12]. The ASIC splits the input current into differently scaled copies which are connected to independent current mirrors. The circuit contains a tuneable pole zero cancellation for the SiPM recovery time, providing an output signal with less than 10 ns FWHM. Any of SiPMs can be powered off. Different gain settings can be configured. Any necessary parameters can be uploaded to ASIC via an SPI interface.

The prototype was tested in August and September of 2018 at the T10 beamline of the CERN PS, which provides charged particles (mostly μ, π, p and e) up to 6 GeV/c [13]. Tests were carried out in conjunction with the High Pressure TPC [14], where the prototype was used in a time of flight (ToF) system. A beam configuration with 0.8 GeV/c

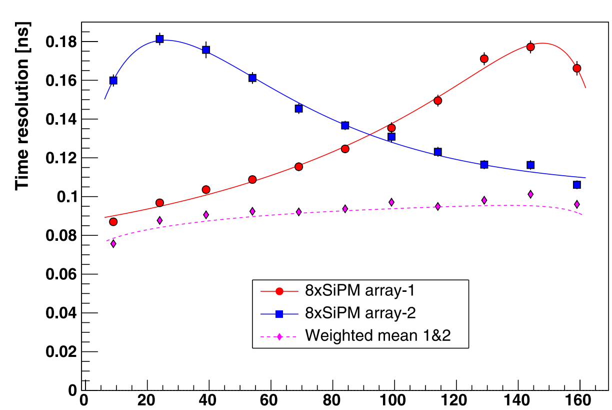

Fig. 3. The timing resolution of a single bar as a function of distance along a bar [9].

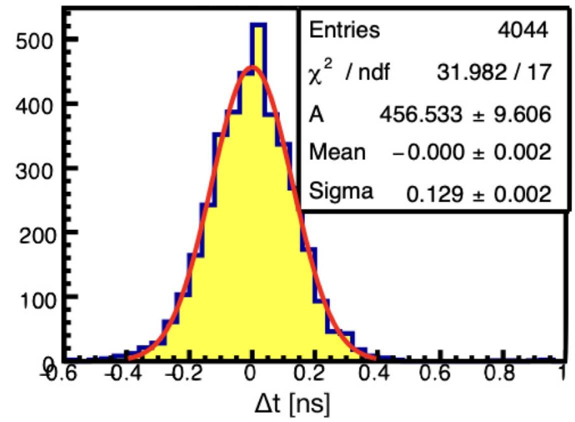

Fig. 4. Time difference distribution between two adjacent bars when a particle interact with both through the overlap region.

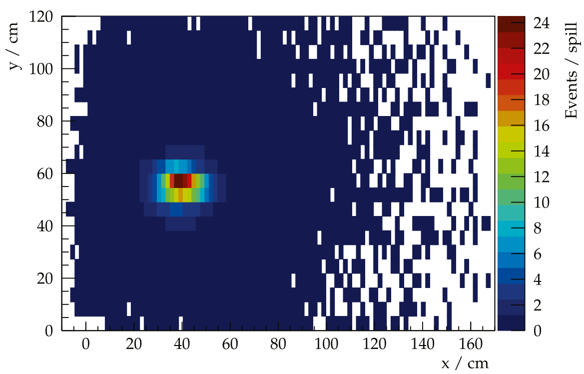

Fig. 5. Reconstructed beam profile.

was primarily used and the set-up was placed off axis so that the TPC system have access to lower momentum protons. A reference time was provided by a beam counter located 10.9 m upstream and consisting of a 40 mm × 40 mm × 5 mm EJ228 plastic scintillator readout by four Hamamatsu R4998 phototubes. The time resolution of the beam counter was measured to be 30 ps. The trigger required signals in three of the four PMTs in the beam counter and one in the prototype to be above 30 mV threshold and coincident in time within 70 ns.

3. Analysis and results

The timestamps of waveforms from the SiPM arrays were determined offline using a constant fraction discriminator (CFD) method. The time resolution for a single bar as a function of distance is shown in Fig. 3. While the distribution for each SiPM array on either end of the bar degrades with distance from the impact point, the weighted mean from both ends becomes more flat with distance and is around 85 ps [7].

The overlap region between bars can be used to calibrate adjacent channels by taking the time difference between signals in both bars. The time difference distribution for two adjacent bars showing signal coincident in time is shown Fig. 4. The resolution is close to expectation at 130 ps/$\sqrt{2} \approx$ 90 ps.

While the mean time of signals on both ends of a bar provides a reference time with a resolution of 85 ps, the time difference of both ends provides the interaction position along the bar. The spatial resolution along a bar can be determined from the timing resolution and the effective propagation speed along bar. It is found to be 1.3 cm, corresponding to an effective propagation speed of 15.5 cm/ns [7]. The beam profile is can be seen in the reconstructed spatial distribution shown Fig. 5.

A ToF measurement with the beam counter 10.9 m upstream provided for particle identification of the beam components. The time difference between the upstream counter and the prototype, Δt, was converted to the particle mass, m, through

$$m^2 = p^2 \left(\left(\frac{\Delta t}{d} c^2 \right)^2 - 1 \right) \tag{1}$$

where $p = 0.8$ GeV/c^2 and $d = 10.9$ m. The different beam components are clearly visible and well separated, as seen in Fig. 6.

4. Summary

The proposed SHiP experiment will perform neutrino physics and explore feebly interacting particles with masses below 10 GeV/c^2. Crucial to the background reduction in SHiP is a dedicated timing detector with a timing resolution of 100 ps or better. One option is a detector consisting of scintillating bars read out by arrays of SiPMs.

We report measurements carried out at the T10 beamline at the CERN PS on a prototype of the SHiP timing detector comprising 22 bars of EJ200 scintillating material readout on both ends by an array of 8 SiPMs. Each bar was 168 cm × 6 cm × 1 cm were staggered vertically with a 5 mm overlap between bars. Analogue signals were readout by a custom pre-amp PCB, MUSIC, and subsequently digitized by SAMPIC. The timing resolution along a single bar was found to be 85 ps and the resolution between adjacent bars was close to expectation at 90 ps. This translates into a spatial resolution of 1.3 cm along a single bar. A ToF measurement with the 10.9 m upstream beam counter provided clear separation of the different beam components.

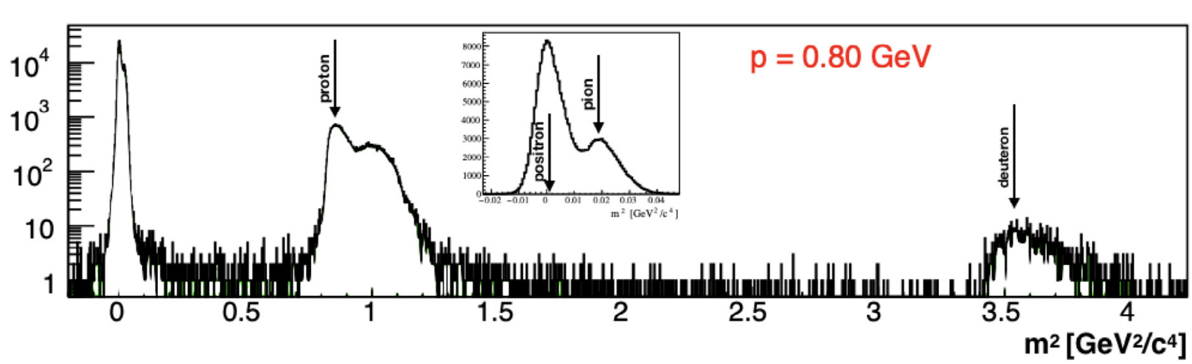

Fig. 6. The m^2 spectrum of the beam obtained through the ToF measurement between the prototype and an upstream beam counter.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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